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Identifying critical sources of phosphorus export from agricultural watersheds

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Abstract

Surface runoff accounts for much of the phosphorus (P) input to and accelerated eutrophication of the fresh waters. Several states have tried to establish general threshold soil P levels above which the enrichment of surface runoff P becomes unacceptable. However, little information is available on the relationship between soil and surface runoff P, particularly for the northeastern United States. Further, threshold soil P criteria will be of limited value unless they are integrated with site potential for runoff and erosion. In response, the Natural Resource Conservation Service (NRCS) developed a P Index (PI), which ranks the vulnerability of fields as sources of P loss in runoff, based on soil P, hydrology, and land use. This study evaluated the relationship between soil and surface runoff P in a study watershed in central Pennsylvania. The relationship was then incorporated into the (PI), and its impact on the identification of critical source areas within the watershed was examined. Using simulated rainfall (6.5 cm h^{-1} for 30 min), the concentration of dissolved P in surface runoff (0.2–2.1 mg l^{-1}) from soils was related (r^2=0.67) to Mehlich-3 extractable soil P (30–750 mg kg^{-1}). Using an environmentally based soil P threshold level of 450 mg kg^{-1} determined from the soil-runoff P relationship, the PI identified and ranked areas of the watershed vulnerable to P loss. The vulnerable areas were located along the stream channel, where areas of runoff generation and areas of high soil P coincide, and where careful management of P fertilizers and manure should be targeted.

Introduction

Phosphorus, an essential nutrient for crop and animal production, can accelerate freshwater eutrophication (Carpenter et al., 1998). Recently, the US Environmental Protection Agency (1996) identified eutrophication as the main problem in waters of impaired quality in the US. Accelerated eutrophication restricts water use for fisheries, recreation, industry, and drinking due to the increased growth of undesirable algae and aquatic weeds and oxygen shortages caused by algal death and decomposition (Carpenter et al., 1998). Periodic surface blooms of cyanobacteria (blue-green algae) associated with eutrophication occur in drinking water supplies and may pose a serious health hazard to animals and humans. Excess nutrients in affected waters have been indirectly associated with recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern US (Burkholder et al., 1992). Neurological damage in people exposed to the toxic volatile chemicals produced by this dinoflagellate has dramatically increased public awareness of eutrophication and the need for solutions (Matuszak et al., 1997). Although N and C are required for eutrophication, their free exchange between the atmosphere and water, and N fixation by blue-green algae, mean that controlling P inputs through source and transport management is critical to limiting freshwater eutrophication (Sharpley and Rekolainen, 1997).

Environmental concern has forced many states to consider developing recommendations for land application of P and watershed management based on the potential for P loss in agricultural runoff (Sharpley et al., 1996; US Department of Agriculture and Environmental Protection Agency, 1999). Currently, these recommendations center on the identification of a threshold soil test P level above which the enrichment of P in surface runoff is considered unacceptable. Agronomic soil testing may not be appropriate or results may need to be interpreted differently for environmental purposes (Sims, 1998). Soil test report interpretations (i.e., low, medium, optimum, high) were based on the expected response of a crop to P; therefore, it cannot be assumed a direct relationship exists between the soil test calibration for crop response to P and for runoff P enrichment potential.

Several studies have found that the concentration of P in surface runoff is related to the amount of P in surface soil (about 0–5 cm) (Pote et al., 1996, 1998; Sharpley, 1995). These and other studies have shown this relationship to be soil type and management dependent (Sharpley et al., 1996). However, most of this research has been limited in geographic area, and little information is available for soils in watersheds with impaired water quality, such as the Chesapeake Bay.

Threshold soil P levels are too limited to be the sole criterion to guide P application and management. For example, adjacent fields having similar soil test P levels, but differing susceptibilities to surface runoff and erosion due to contrasting topography and management, should not have similar P management recommendations. Also, most of the P exported from agricultural watersheds generally comes from only a small part of the landscape during a few relatively large storms (Pionke et al., 1997). Therefore, threshold soil P values will have little meaning unless they are used in conjunction with an estimate of a site=s potential for surface runoff and erosion (Gburek and Sharpley, 1998). Even in regions where subsurface flow pathways dominate, areas contributing P to drainage waters appear to be localized to soils with high soil P saturation and hydrological connectivity to the drainage network (Schoumans and Breeuwsma, 1997).

The Natural Resource Conservation Service (NRCS), in cooperation with research scientists, has developed a P Index (PI) as a screening tool for use by field staff, watershed planners, and farmers to rank the vulnerability of fields as sources of P loss in surface runoff (Lemunyon and Gilbert, 1993). The PI accounts for source and transport factors controlling P loss in surface runoff and ranks sites according to the risk of P movement. It is intended for use as a tool for field personnel to easily identify agricultural areas or practices that are most vulnerable to P loss, allowing farmers more flexibility in developing P control strategies.

This paper describes research that quantifies the relationship between P in soil and surface runoff. This relationship is then incorporated into the PI to more accurately reflect P export potential from an upland agricultural watershed in Pennsylvania.

Materials and methods

Study area

The study was conducted on a 39.5-ha subwatershed (FD-36) of Mahantango Creek, which is tributary to the Susquehanna River and ultimately the Chesapeake Bay (Fig. 1). FD-36 is typical of upland agricultural watersheds within the nonglaciated, folded and faulted, Appalachian Valley and Ridge Physiographic Province. Soils are mostly Alvira (Typic Dystrochrepts), Berks (Typic Dystrochrepts), Calvin (Typic Dystrochrepts), Hartleton (Typic Hapudults), and Watson (Typic Fragiudults) channery silt loams, with slopes ranging from 1 to 20% (Fig. 1). Climate is temperate and humid, average rainfall is approximately 1100 mm year^{-1}, and streamflow is about 450 mm year^{-1}.

The watershed has mixed land use (50% soybean, wheat, or corn; 20% pasture; 30% woodland). Other than rotating the crops between fields, land management is relatively constant from year to year. In the last 5 years, several fields north of the stream received about 100 kg P ha^{-1} from swine slurry each spring and no fertilizer P. South of the stream, approximately 85 kg P ha^{-1} from poultry manure was applied to cropland each spring.

In July 1996, soil samples (0–5 cm depth) were collected on a 30-m grid over the watershed. The samples were air dried, sieved (2 mm), and the Mehlich-3 soil P concentration determined (Mehlich, 1984).

Surface runoff simulation

Forty soil blocks (100 cm long, 20 cm wide, and 30 cm deep) were collected from FD-36 in September 1997 (Fig. 1). The locations were on Berks, Calvin, and Watson soils, located in hydrologically active areas potentially contributing surface runoff to the stream channel, and covered a range in land management and Mehlich-3 P content (10–800 mg P kg^{-1}). The soil

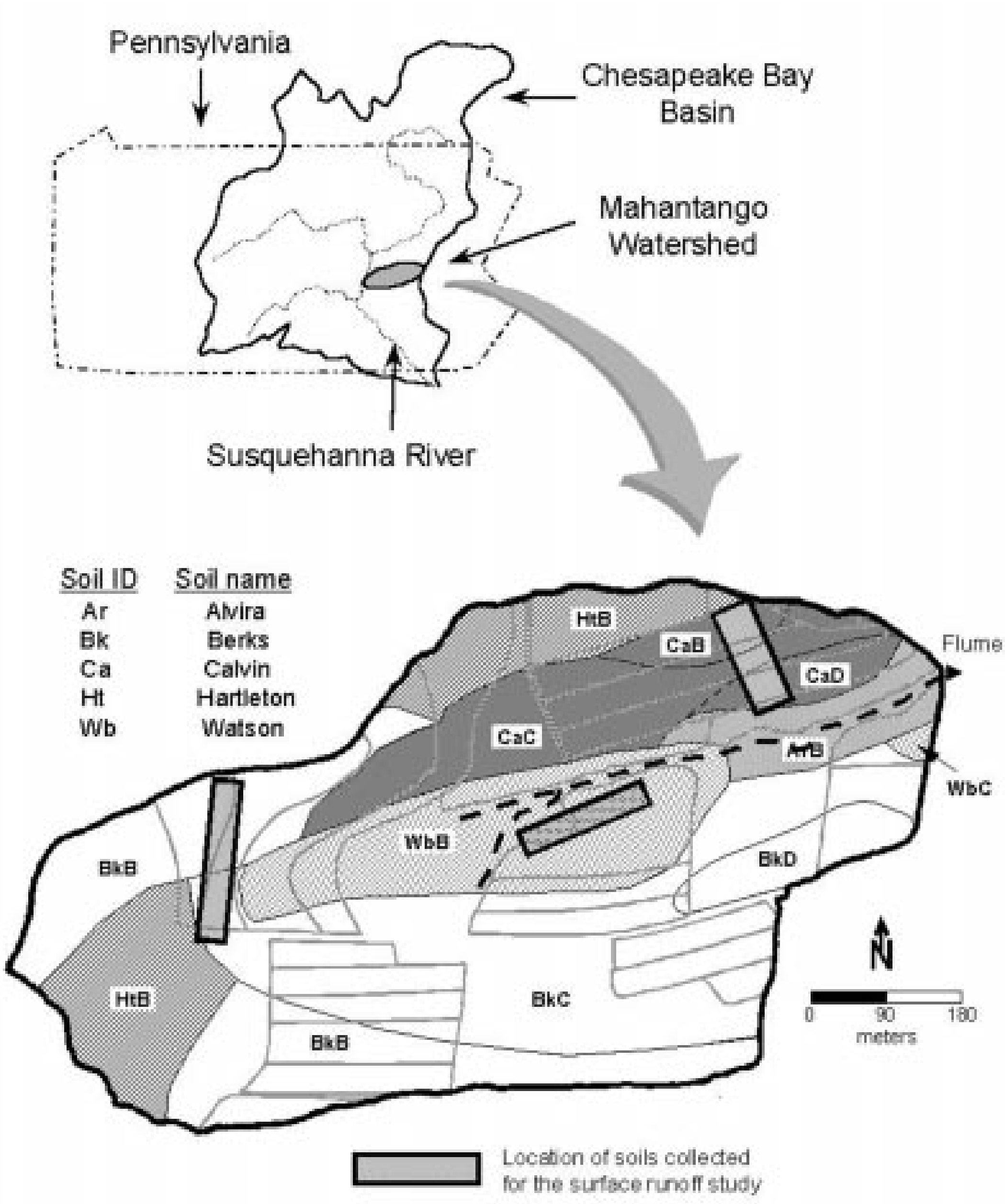

Figure 1. Location, soil type, field boundaries, and soil collection sites for the surface runoff study in watershed FD-36.

blocks were brought to the ARS Pasture Systems and Watershed Management Research Laboratory, University Park, PA, and three simulated rainfall events (6.5 cm h^{-1} for 30 min) were applied at 1-day intervals. Soil samples (0–5 cm depth) taken prior to rainfall were analyzed for Mehlich-3 P as described above. Surface runoff from the boxes was collected, filtered (0.45 mm), and the dissolved P measured by the molybdenum-blue method of Murphy and Riley (1962).

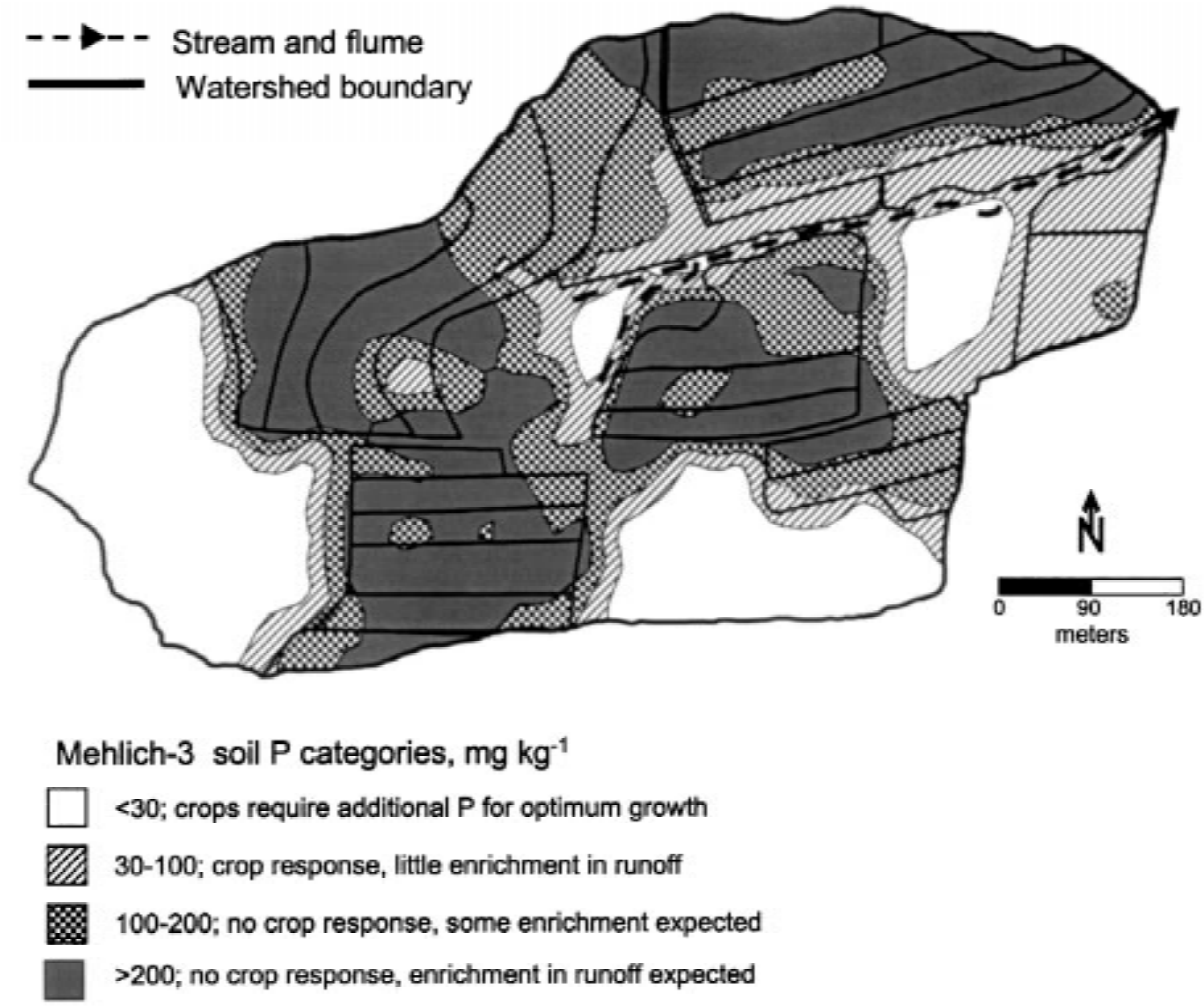

Figure 2. Distribution of Mehlich-3 soil P (0–5 cm soil depth) for FD-36.

Results and discussion

Soil test P distribution

Based on the range of the 30-m grid sampling, Mehlich-3 soil P ranged from 7 to 788 mg P kg^{-1} across FD-36. The pattern of Mehlich-3 P values over FD-36 is generally a function of land use and field boundaries within the watershed (Fig. 2). Soils in wooded areas have low values of Mehlich-3 P ($<$30 mg P kg^{-1}), grazed pastures have values between 100 and 200 mg P kg^{-1}, and cropped fields receiving manure and fertilizer applications are, in most cases, above 200 mg P kg^{-1}. Near-stream areas, ranging about 30 m on either side of the channel, are wet for much of the year which limits their productive value, and thereby amounts of P applied. Thus, Mehlich-3 P concentrations in these near-stream areas were generally $<$100 mg kg^{-1} (Fig. 2). Based on soil test P alone, there would be no yield response to P application ($>$50 mg kg^{-1} Mehlich-3 P; Beegle, 1999) on 86% of the cropped area of the watershed.

Relating surface runoff and soil phosphorus

The soil test levels indicate only the magnitude of the source of P in the soil. The relationship between soil P content and transport of P in surface runoff was evaluated using the 40 undisturbed soil blocks collected from FD-36. The average dissolved P concentration

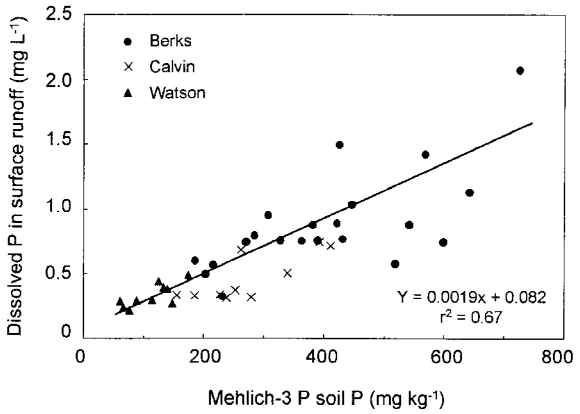

Figure 3. Relationship between dissolved P concentration in runoff and Mehlich-3 P content of soils from watershed FD-36.

of three surface runoff events from each soil was related to Mehlich-3 P content (0–5 cm depth) prior to rainfall (r^2 = 0.67; Fig. 3). The relationship between surface runoff P and soil test P appears similar for the three soils studied. This relationship can be used to determine the critical soil test level where an unacceptable dissolved P concentration in surface runoff could occur if there is runoff. For example, an upper limit of 1 mg l^{-1} has been used for point-source discharge from sewage treatment plants (US Environmental Protection Agency, 1996). The 1-mg l^{-1} dissolved P concentration level would be exceeded if Mehlich-3 soil P was greater than 450 mg kg^{-1} (Fig. 3). Although we are not proposing a critical concentration of 1 mg l^{-1} dissolved P in surface runoff, this scenario shows how the relationship may be used to establish environmentally based threshold soil test P levels. The current PI (Lemunyon and Gilbert, 1993) uses a soil test level of 200 mg kg^{-1} as the critical level. This level would support a dissolved P concentration of about 0.5 mg l^{-1}. The decision about 'acceptable and unacceptable' levels of P in runoff from agricultural land is complex and will have to involve many stakeholders. However, when an acceptable P level in runoff is decided, these experimentally derived relationships are essential to estimating the soil test P levels to be used in the PI.

The phosphorus index

The Phosphorus Index as used in this study was modified from the original PI described by Lemunyon and Gilbert (1993) to more accurately represent P source and transport relationships and potential for surface runoff to contribute to streamflow (Table 1; Gburek et al., 2000). Two major changes were introduced. First, transport factors were made multiplicative rather than additive because these better represent actual site vulnerability to P loss. For example, if surface runoff does not occur at a particular site, its vulnerability should be low regardless of the soil P content. In the original PI, a site could be ranked as very highly vulnerable based on source factors alone, even though no surface runoff or erosion occurred.

Second, an additional transport characteristic reflecting distance from the stream was incorporated into the PI. The contributing distance categories in the revised PI are based on a hydrological analysis of the probability (or risk) of occurrence of a rainfall event of a given magnitude which will result in surface runoff to the stream (Gburek et al., 2000). A higher risk of surface runoff contributing P to the stream channel is associated with the shorter distances from the stream and small storms because of their high frequency of occurrence. Storms large enough to cause runoff long distances from the stream occur much less often, and therefore, pose a lower risk of P loss to the stream. These categories for the FD-36 watershed are shown in Fig. 4 in terms of the frequency at which runoff is likely to occur. For example, we would only expect runoff to the stream from the white areas in Fig. 4 on the average of once every 10 years.

The modified PI was applied on a 25-m^2 cell scale over the FD-36 watershed. Erosion and surface runoff class were obtained from Soil Survey descriptions of each soil type in the watershed. Mehlich-3 soil P values from the 30-m grid sampling were used to determine the soil test P for each cell. Soil P categories were initially based roughly on expected crop yield response and perceived P enrichment of surface runoff: $<$30 mg kg^{-1}, crops require additional P for optimum growth; between 30 and 100 mg kg^{-1}, there will generally not be a crop response to P application but little enrichment of P in surface runoff (probable crop response decreases as Mehlich-3 P increases from 30 to 100 mg kg^{-1}); between 100 and 200 mg kg^{-1}, there will be no response to applied P while some enrichment of P in surface runoff may occur; $>$200 mg kg^{-1}, levels are considered excessive in terms of crop requirements and enrichment of P in surface runoff can be expected (Beegle, 1999; Sharpley et al., 1996). The upper threshold value of 200 mg kg^{-1} is about twice the maximum crop response value. A similar approach has been used by several states to develop environmental threshold soil P levels (Sharpley et al., 1996).

Table 1. The modified Phosphorus Index to rate potential P loss in runoff using site characteristics

Transport Characteristics	Weight	Phosphorous Loss Rating (value) None (0.6)	Low (0.7)	Medium (0.8)	High (0.9)	Very High (1.0)
Soil erosion	1.0	Not applicable	< 11 Mg/ha	11–22 Mg/ha	23–34 Mg/ha	> 34 Mg/ha
Irrigation erosion	1.0	Negligible	Infrequent irrigation on well-drained soils	Moderate irrigation on soils with slopes < 5%	Frequent irrigation on soils with slopes of 2 to 5%	Frequent irrigation on soils with slopes > 5%
Runoff class	1.0	Negligible	Very low or low	Medium	High	Very high
		None (0.2)	**Low (0.4)**	**Medium (0.6)**	**High (0.8)**	**Very High (1.0)**
Return period/ contrib. distance	1.0	> 10 yr > 152 m	6–10 yr 152–122 m	3–5 yr 122–76 m	1–2 yr 76–30 m	< 1 yr < 30 m
Source Characteristics	**Weight**	**None (0)**	**Low (1)**	**Medium (2)**	**High (4)**	**Very High (8)**
Mehlich-3 soil test P	1.0	< 10 mg P/kg	10–30 mg P/kg	30–100 mg P/kg	100–200 mg P/kg	> 200 mg P/kg
P fertilizer rate	0.75	None applied	< 17 kg P/ha	18–45 kg P/ha	46–73 kg P/ha	> 73 kg P/ha
Fertilizer application method	0.5	None applied	Placed with planter deeper than 5 cm	Incorporated immediately before crop	Incorporated > 3 mos or surface applied < 3 mos before crop	Surface applied >3 mos before crop
Organic P rate	1.0	None applied	< 17 kg P/ha	18–45 kg P/ha	46–73 kg P/ha	> 73 kg P/ha
Organic P application method	1.0	None	Injected deeper than 5 cm	Incorporated immediately before crop	Incorporated > 3 mos or surface applied < 3 mos before crop	Surface applied > 3 mos before crop

PI = (erosion rating x runoff rating x return period rating†) x Σ (source characteristic rating x weight)

†Note that ratings for Return Period are different than those for Erosion and Runoff characteristics

PI	Site P Loss Vulnerability
<5	Low
5–8	Medium
9–22	High
>22	Very high

Table 2. Phosphorus Index generalized interpretations

PI rating	Generalized interpretation
< 5	Low: potential for P loss. If current farming practices are maintained, there is low probability of adverse impacts on surface waters.
5–8	Medium: potential for P loss. Chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize probability of P loss.
9–22	High: potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and a nutrient management plan are needed to minimize probability of P loss.
> 22	Very high: potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a nutrient management plan must be implemented to minimize P loss.

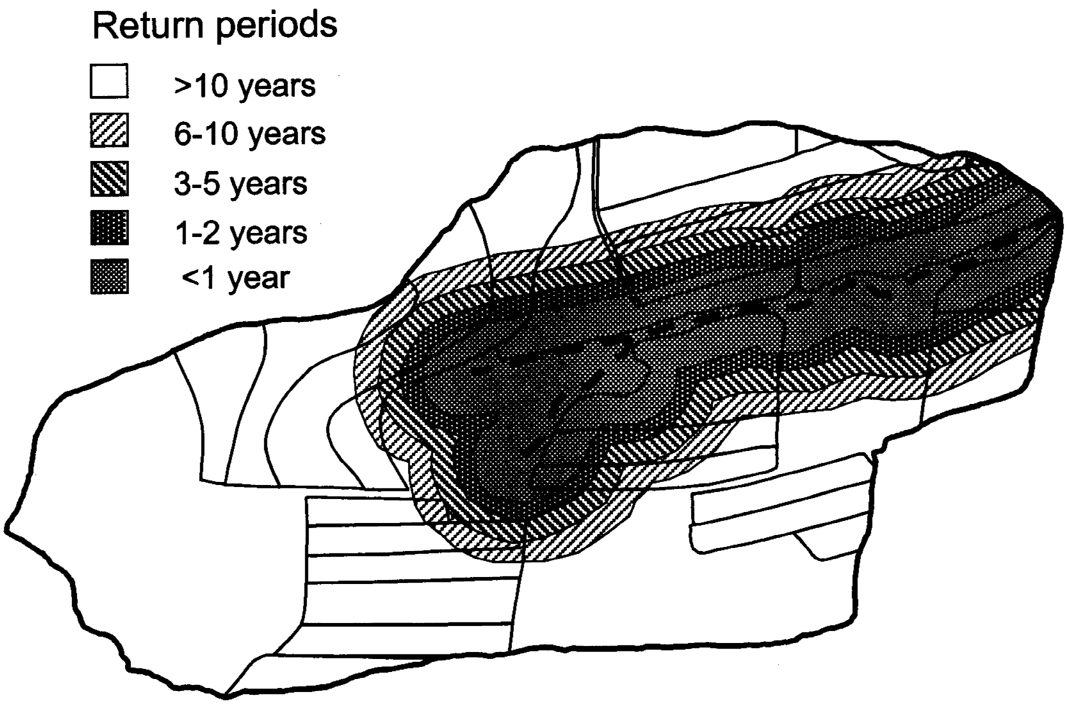

Figure 4. Surface runoff potentials controlling P transport from FD-36.

Management information required in the PI about the rate and method of P application as fertilizer or manure was obtained from annual surveys of farmers operating within the FD-36 watershed. The PI value for each 25-m^2 cell is the sum of the weighted values of all source factors, multiplied by the transport factors (Table 1). The total PI rating values were categorized into four classes of site vulnerability to P loss, ranging from low to very high risk (Table 2).

Applying the phosphorus index

The PI values calculated for the FD-36 watershed are shown in Fig. 5. Areas close to the stream channel, where there is a high probability of surface runoff to the stream and which also had high Mehlich-3 soil test P values (> 200 mg kg^{-1}), were ranked medium to high P loss vulnerability (Fig. 5a). It was observed that these areas did contribute surface runoff to the stream channel during most storm flow events in FD-36 during 1996 and 1997. Other areas of the watershed not

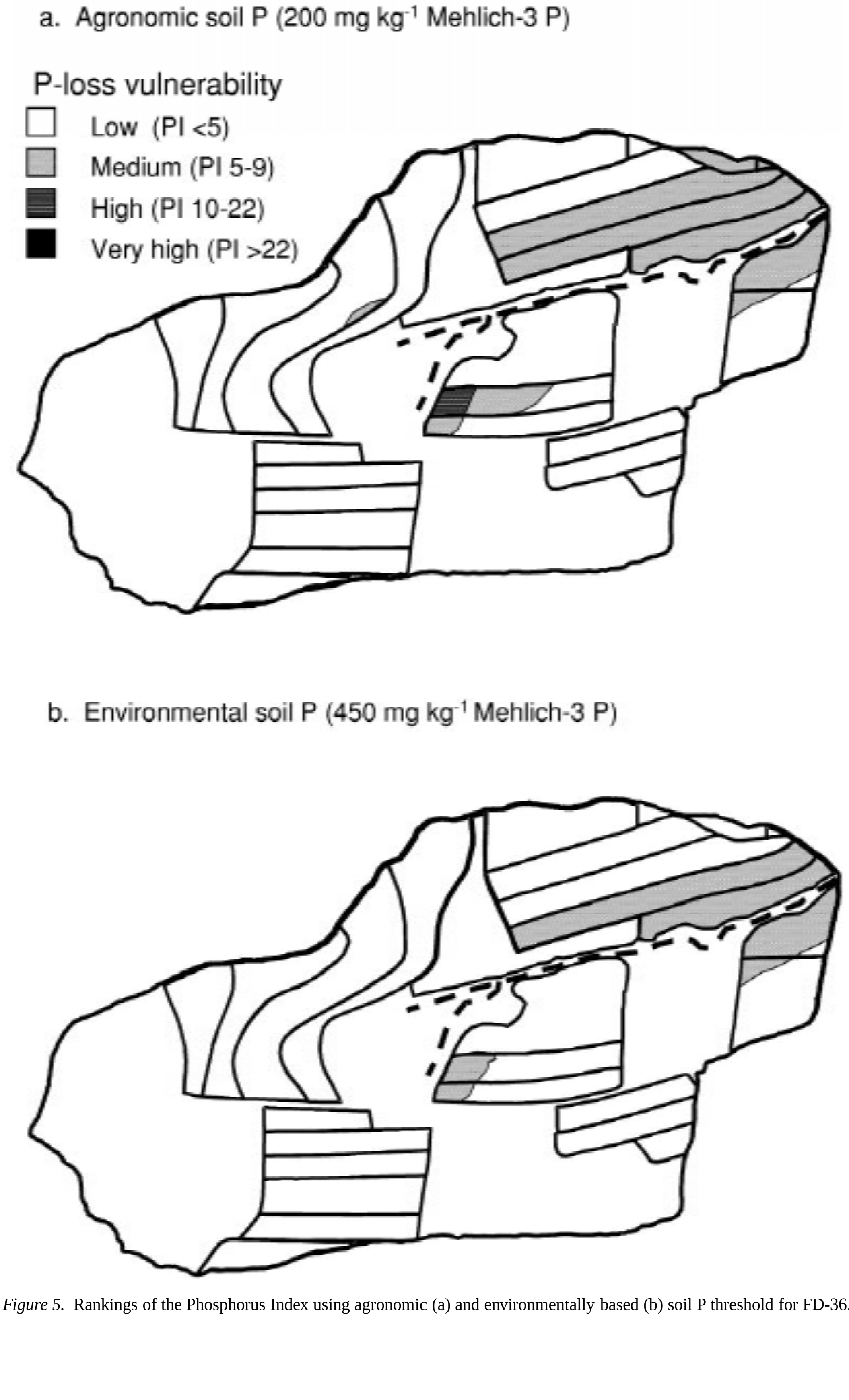

Figure 5. Rankings of the Phosphorus Index using agronomic (a) and environmentally based (b) soil P threshold for FD-36.

contributing surface runoff to the stream channel were ranked as having a low vulnerability.

We then applied the PI to FD-36 using a Mehlich-3 soil P threshold value of 450 mg kg^{-1} for the very high category (Fig. 5b). This was based on the relationship shown in Fig. 3 and on a limit of 1 mg l^{-1} dissolved P concentration in surface runoff. The main difference in PI ranking between the two soil P criteria was the reduction of high to medium vulnerability areas. Although a Mehlich-3 soil threshold P level of 450 mg kg^{-1} is not proposed as a general environmental threshold value, it is clear that the PI is sensitive to both source and transport factors.

Conclusions

The results of this research show that the concentration of dissolved P in surface runoff is related to the Mehlich-3 P concentration in surface soil. The relationship can be used to define environmentally-based threshold soil P levels once a limit for P concentration in surface runoff is established. Further:

- this relationship can be used to quantify the soil P categories of the PI, a key input for determining the vulnerability of P loss to surface runoff;
- critical source areas or 'hot spots' of P loss from the watershed were identified by the PI and were generally located near the stream channel where areas of surface runoff and high soil P coincided;
- the PI, as modified by Gburek et al. (2000), more accurately represents the surface runoff-soil P relationship and potential for surface runoff to contribute to streamflow. The modified PI indicated where P-based management of fertilizers and manures should be targeted for most effective control.

Much work is still needed to develop comprehensive management strategies that control P loss from fields and/or watersheds by incorporating all hydrological factors, particularly source-area controls of runoff generation. Modeling tools and field data are not sufficiently available to integrate all aspects of hydrological controls from the flow perspective alone, much less from that of their interactions with water quality. However, we can draw conclusions based on results from the studies presented.

In the most simple sense, the intersection of surface runoff source areas and areas of high soil P within a watershed generally creates the critical source areas controlling most P export. Thus, it appears that P export may be most efficiently managed by focusing primarily on control of soil P levels in the hydrologically active zones most likely to produce surface runoff. The corollary is that soil P levels are less important in the other areas when it comes to controlling P export from a watershed. There are some exceptions to this. For example, P transport by preferential subsurface flow in coarse-textured soils. Nonetheless, the typical case suggests that differing levels of P management may be necessary for different areas of the watershed, an approach to land management that will have to be addressed by action agencies.

If source-area identification and surface runoff and erosion control technology are not used, conventionally applied remediation measures may not reduce P loss from the landscape and may not be a cost-effective approach. A technically sound framework must be developed that identifies the sources and transport pathways controlling P export from agricultural watersheds so that optimal remedial strategies can be targeted to critical areas of the farm or watershed.

The modified Phosphorus Index will go a long way toward providing reliable technology to identify and target critical source areas of P export from watersheds for more effective remediation. But we must keep in mind that while we are developing such tools to address the immediate problem of P management at the watershed scale, we must also be working to bring the overall farm systems into P balance. This is the long-term answer to P management at the watershed scale.

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